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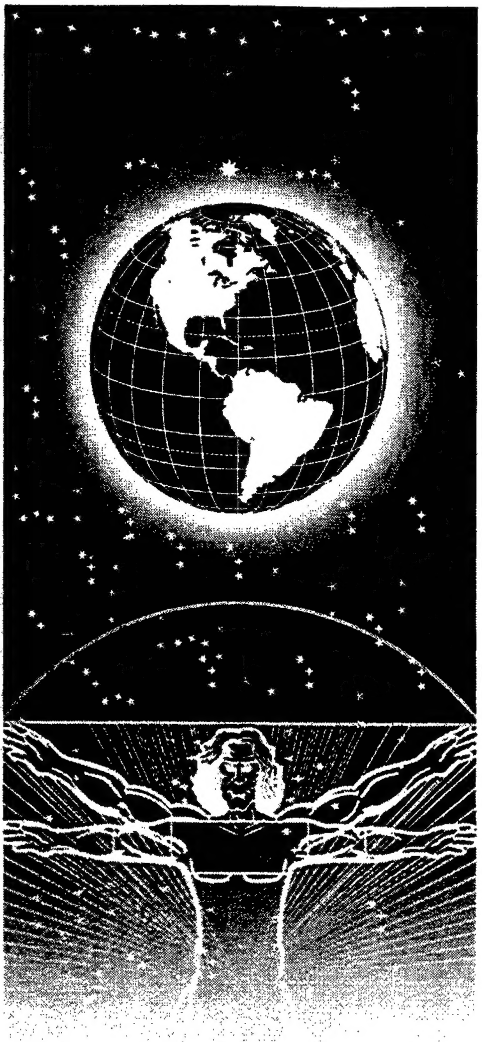

UNITED STATES AIR FORCE RESEARCH LABORATORY

AN EVALUATION OF PILOT UPLOOK FOR A. U.S. AIR FORCE AND U.S. NAVY HELMET-MOUNTED CUEING SYSTEM

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FINAL REPORT FOR THE PERIOD OCTOBER 1995 TO DECEMBER 1996

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TECHNICAL REVIEW AND APPROVAL

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
Air Force Research Laboratory

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The goal of the Uplook Angle Study was to determine human limitations in head and neck range of motion in the vertical plane while seated in a variety of ejection seats, and while wearing different ensembles of protective equipment. Although some information on range of motion of the neck is available in the literature, none are relevant to the encumbered and high-G conditions that fighter pilots encounter.

Data from the study will serve as input into a joint service system which will enhance aircraft lethality and survivability by reducing the amount of time aircrews need to acquire targets. Information from helmet-mounted sights and weapons systems will be projected to small displays near the eye, allowing aircrews to react quickly, especially in high threat envrionments. Pilots will be able to aim weapons by simply moving their heads and designating the target. The system will also display a variety of other information about sensors, targets, and aircraft status, which will enable pilots to stay "eyes out of the cockpit" as much as possible; greatly enhancing their visual search capability and overall situation awareness.

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PREFACE

This study was conducted in support of the Air Force/Navy Joint Helmet-Mounted Cueing System (JHMCS) program, which is directed by Aeronautical Systems Center's JHMCS Integrated Product Team (ASC/LYC). The authors wish to acknowledge the following contributors and thank them for their help: Jerry Woods (UDRI), for collecting the data at Nellis AFB and editing the data upon his return; Greg Zehner (AL/CFHD), for helping set up the analysis, and providing consultation on the interpretation of the analysis; Dr. Joe W. McDaniel (AL/CFHD), for assistance in designing the experiment and reviewing and editing this report; Patrick Files (Sytronics, Inc.), for helping to edit this report.

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INTRODUCTION

The Uplook Angle study was undertaken in order to determine human limitations in head and neck range of motion in the vertical plane, while seated in a variety of ejection seats, and while wearing different ensembles of protective equipment. Although some information on range of motion of the neck is available in the literature, none are relevant to the encumbered and high-G conditions that fighter pilots encounter.

This study was conducted in support of the Air Force/Navy Joint Helmet-Mounted Cueing System (JHMCS) program, which is directed by Aeronautical Systems Center's JHMCS Integrated Product Team (ASC/LYC).

Data from the study will serve as input into a joint service system which will enhance aircraft lethality and survivability by reducing the amount of time aircrews need to acquire targets. Information from helmet mounted sights and weapons systems will be projected to small displays near the eye, allowing aircrews to react quickly, especially in high threat environments. Pilots will be able to aim weapons by simply moving their heads and designating the target. The system will also display a variety of other information about sensors, targets, and aircraft status, which will enable pilots to stay "eyes out of the cockpit" as much as possible, greatly enhancing their visual search capability and overall situation awareness.

OBJECTIVE

The JHMCS will be integrated into existing aircraft (F-15, F/A-18, F-16, F-22, F-14, and AV-8B) with varying parameters defining a reference location for the pilot. Seat-back angle and relative Head Rest position in existing aircraft vary a great deal. Protective equipment also differs across platforms and services. Each of these factors influence human range of neck motion and constrain the pilot's ability to cue the JHMCS. This situation may force the pilot to maneuver the aircraft prior to engaging the target and would degrade the positive effects of the JHMCS. Therefore, to enhance the head tracking scheme to be used with the JHMCS, it will be necessary to consider human limitations in neck flexibility during the design of the cueing system.

The Uplook Angle Study was approached in two phases. First, since the single- and double-circle air-to-air engagements were deemed to be the most radical or difficult cueing tasks, a simple X-Z plane (vertical) measure of dorsal neck flexion was undertaken. This phase, Phase I, is described in the main body of this report. The second phase of the study, Phase II, was to establish the full three-dimensional head motion envelope the pilot was able to obtain. Phase II (Motion Envelope) testing uses a motion-sensor tracking system to determine the regions (not only in the vertical plane, but side-to-side in an arc movement as well) within which a pilot can point his or her helmet. A description of Phase II appears in Appendix B.

This study was not intended to identify the restrictions placed on the pilot's range of motion by a particular helmet. After a physiological baseline has been established (expressed as an uplook angle), the general overall effect of selected life support equipment items was determined. These differences will be expressed in angular terms.

The body of this report documents Phase I testing; Appendix B documents Phase II testing.

PHASE I: HEAD TILT RANGE OF MOTION

TEST DESIGN

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Subjects

The primary goal of the Uplook Angle study was to measure dorsal flexion capability (in a vertical plane) of the current aircrew population in order to establish a physiological baseline. It must be kept in mind that this is not a measure of visual field. Eye movement is not being considered. For helmet mounted systems, the position or range of motion of the helmet is the area of concern.

The subject sample was intended to be representative of the aircrew population as defined by the Joint Primary Air Training System (JPATS) requirement. Civilians who were not representative of potential pilots in accordance with the JPATS program (particularly the Height and Weight requirements) were excluded from the testing. While pilots with high-g flying experience[1] were preferred, the limited availability of flyers, and the need for extremely small individuals to represent the small JPATS pilots, required that the test sample be supplemented with civilian data.

The final sample included 44 men (23 of whom were rated pilots) and 30 women. Subjects were drawn from a variety of sources, including a subject pool maintained by Logicon Technical Services, Inc. (LTSI), a Wright-Patterson Air Force Base contractor. Subjects from the subject pool were, in general, Caucasian males and females of college age who were drawn from the local community. In addition to the subject pool, local military and civilian volunteers were also solicited for the study through LTSI.

The thirty female subjects participated in the Phase I testing only. Of the 44 males, 22 participated in Phase I, including one pilot from the 422 Squadron 57 TG, Nellis Air Force Base, Nevada. The remaining 22 male subjects were pilots who participated in both the Phase I and the Phase II portions of the testing. These pilots were from the 57 TG at Nellis.

The female test sample does not include any pilots with high-g experience. Female fighter pilots were unavailable for testing. Table 1 provides a simple breakdown of the study participants.

[1] "High-g" experience refers to experience flying under conditions where the effects of gravity are significantly increased (eight to nine G).

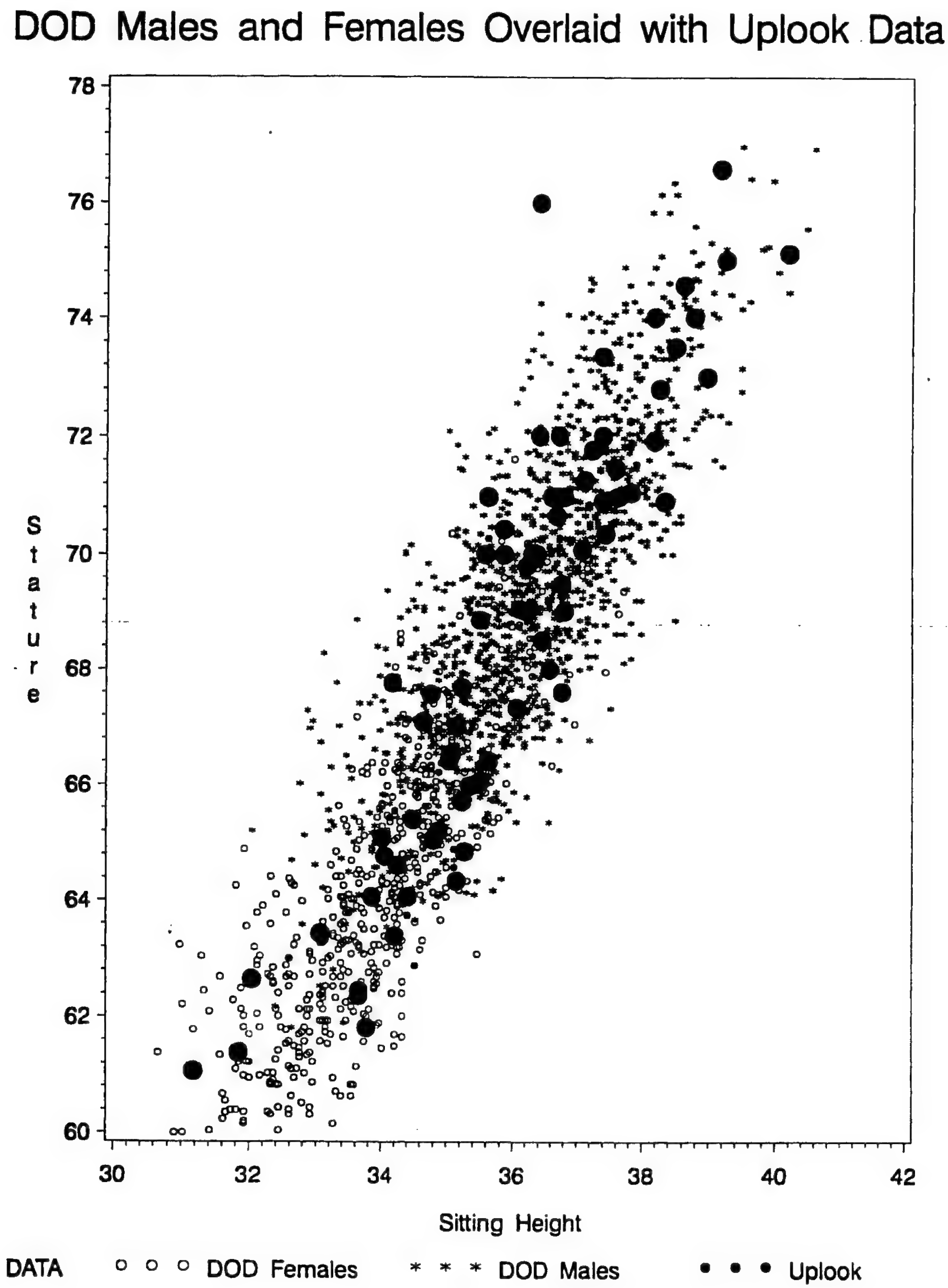
Table 1: Test Subjects

Number	Male/Female	Pilot?	High-Gz Exp?	Phase I?	Phase II?
1	F	Y	N	Y	N
29	F	N	N	Y	N
3	M	Y	N	Y	N
19	M	N	N	Y	N
1	M	Y	Y	Y	N
21	M	Y	Y	Y	Y

Anthropometry

Seventeen traditional anthropometric dimensions were measured on each subject in order to 1) provide descriptive body size data for the sample, 2) select the appropriate sizes (according to item technical orders) of each life support item, and 3) determine if there was a relationship between body size (for example, neck length and circumference) and neck range of motion. A description of the dimensions and a copy of the data sheet are included in Appendix A. Figure 1 on the following page is a bivariate plot of the Stature and Sitting Height of the JPATS populations. The subjects from the Uplook Study are superimposed over the plot.

Figure 1:



Data are in inches.

TEST EQUIPMENT

The Ejection Seats

Two Air Force ACES II seats were used to represent the F-15 (Seat 1) and F-16 (Seat 2) configurations. A Navy F-18 NACES (Seat 3) ejection seat was also used in this study. The seat back angle orientation of the ACES II is quite different in the F-15 and the F-16, and the NACES seat geometry is very different than the ACES II seat in either the F-15 or F-16 orientation. The NACES seat pan moves separately from the seat back and head box. All subjects were adjusted in the seat until their head was centered vertically on the head box. Also, the head box in the NACES seat is forward of the seat back tangent, while the ACES seat back and head box are in the same plane.

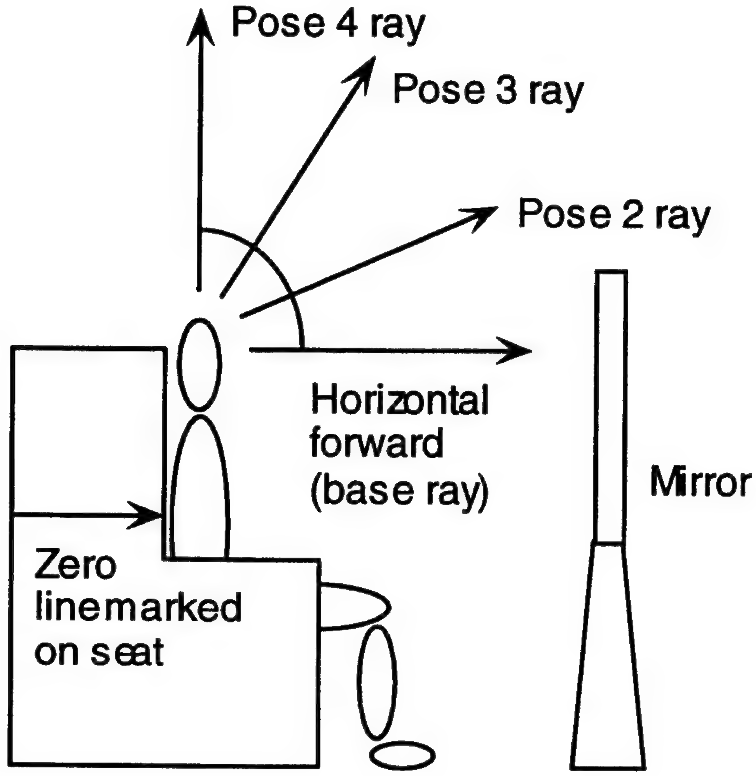
Each subject donned the appropriate harness in order to be correctly strapped in the ejection seat prior to data collection.

The "Zero" Line

The zero degree reference line was established as parallel to the aircraft waterline and was used to establish the seat pan/seat back angle for each seat (see Figure 2). The zero line was located and marked on each ejection seat such that it was visible while a subject performed the uplook postures. Encumbered and unencumbered dorsal flexion for each subject was measured relative to the zero line in each of the ejection seats.

Several anatomical landmarks were located, by palpation or visual examination, and were covered with small, blue, adhesive-backed dots, placed on the subjects' faces and on their helmets. These landmarks were essential for defining head orientation and for establishing the baseline reference rays used to measure the uplook angle. Figure 2 below shows the reference rays for each uplook pose.

Figure 2: Reference rays used in uplook angle measurement



Life Support Equipment

One requirement of the study was measuring current dorsal flexion capability of the same aircrew population encumbered by life support equipment. This life support equipment consisted of 1) the HGU-55/P helmet and the MBU-12/P or MBU-5/P oxygen mask, 2) the HGU-86/P helmet, 3) the HGU-55/P helmet and MBU-12/P or MBU-5/P mask with the LPU-21B/P life preserver, and 4) the HGU-86/P helmet with the LPU-21B/P life preserver.

The Life Support equipment (personal protective equipment, or PPE) tested during the Head Tilt Range of Motion testing is described below.

Standard Helmet and Mask

All sizes of HGU-55/P and MBU-12/P were available for testing. The HGU-55/P is the three-size, standard issue Air Force fighter/attack aircrew helmet. The 55/P was tested with the MBU-12/P or MBU-5/P oral/nasal oxygen mask. The MBU-12/P is the current issue oxygen mask, which is not easily customized. Individuals who cannot be fit in the MBU-12/P mask receive a customized version of the MBU-5/P oxygen mask.

HGU-86/P Helmet

The HGU-86/P is a prototype helmet developed by the F-22 Special Project Office (SPO) for use by F-22 aircrew members. The HGU-86/P was designed to be a stand-alone equipment item, and was tested as such during the Head Tilt Range of Motion and Angular Range of Motion testing. Although the F-22 SPO has developed an oxygen mask to be worn by F-22 aircrews, a prototype of the mask was not available for testing.

The F-22 SPO loaned a full range of helmets to the investigators for this study. A representative of the F-22 SPO provided investigators with hands-on instruction on how to properly fit the helmet. These investigators are very familiar with the helmets and with helmet-fitting procedures from previous research programs. A SPO representative reviewed the fitting process and gave her approval.

Table 2 provides the sizing information for the helmets and masks.

Table 2: Helmet and Mask Sizing

		SIZING CHARTS		
		THE HGU-55/P HELMET		
Head Length (Inches)	(Cm)	Head Breadth (Max.) (Inches)	(Cm)	Helmet Size
7.2 - 7.8	18.3 - 19.8	6.2	15.7	Medium
7.7 - 8.3	19.5 - 21.0	6.5	16.5	Large
8.2 - 8.7	20.8 - 22.1	6.8	17.3	Extra Large

	THE HGU-86/P HELMET	
Helmet Size	Head Breadth (mm)	Head Length (mm)
Small	137 to 160	179 to 194
Medium	137 to 160	190 to 207
Large	145 to 170	202 to 218

	THE MBU-12/P MASK	
Size (Inches)	Face Length (Inches)	Face Length (cm)
Short	3.6 - 4.0	9.1 - 10.16
Regular	4.0 - 4.4	10.2 - 11.176
Long	4.4 - 4.8	11.176 - 12.19
Extra Long	4.8 - 5.1	12.19 - 12.954

The Flight Suit

Several sizes of the CWU-27/P flight suit were made available for the non-pilot test subjects. In addition to the CWU-27/P, several additional sizes were available in the Enhanced Air Force Flight Suit (EAFFS) and the Modified Enhanced Air Force Flight Suit (MEAFFS). Because the sole purpose of the flight suit was to provide a fit in a garment equivalent to one which would be used in an aircraft cockpit, the type of flight suit a subject wore (CWU-27/P versus EAFFS versus MEAFFS) was deemed irrelevant, and the flight suits were considered interchangeable.

Harnesses

The Navy harness (used for the NACES ejection seat) exists in an extensive range of sizes (approximately 26 sizes in all). While many of those sizes were not available, the sizes which were available accommodated our subjects well enough for us to see the effect of the harness on neck motion. The sizes available were the Small/Short (SS), Small/Regular (SR), Medium/Regular (MR), and the Extra Large/Extra Long (XXL).

Life Preserver Unit (LPU-21B/P)

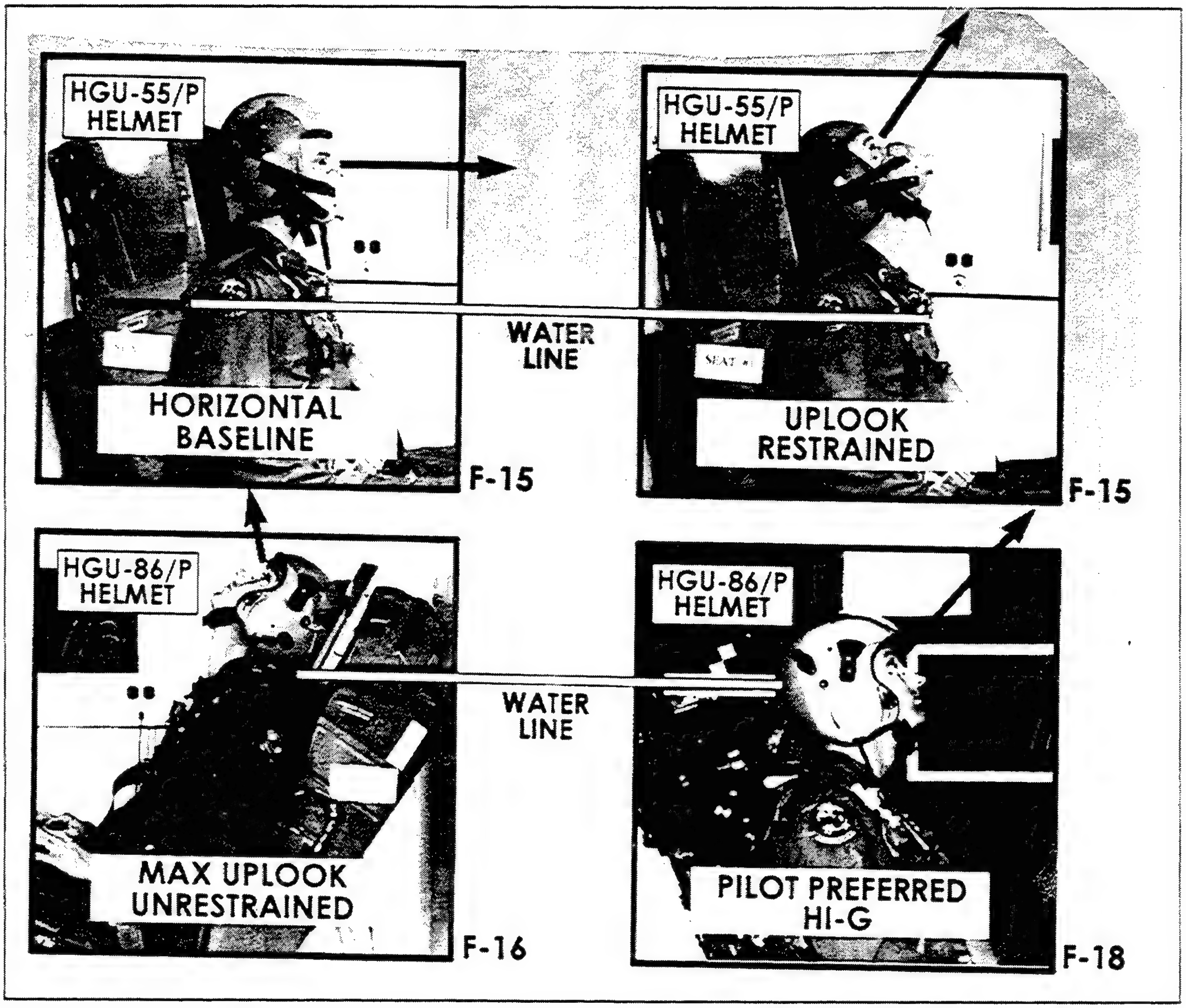
The LPU-21B/P flotation assembly consists of two independent flotation chambers. One chamber consists of the left waist lobe joined by a tube to the right collar lobe. The other chamber consists of the right waist lobe joined by a tube to the left collar lobe. The fire-retardent aramid cloth casing assembly is secured around the wearer's waist by the front connector assembly.

Possible impact of the Life Preserver (LPU-21B/P) on dorsal flexion capability was also considered. Subjects were tested in the LPU-21B/P life preserver in each of the three seats wearing the HGU-55/P and HGU-86/P helmets. After a subject had completed uplook in the unencumbered and helmeted conditions, the LPU was added and uplook was recorded for each helmet/LPU equipment combination for the subjects.

SUMMARY FOR PHASE 1

Four uplook postures were measured during each iteration of the testing. These were: 1) forward line of sight, 2) restrained uplook, 3) maximum restrained uplook, and 4) High-G uplook. Figure 3 below shows the four uplook poses. Each pose is discussed in the paragraphs below.

Figure 3: Uplook Poses



The four poses were measured repeatedly in the following conditions for Phase I of the study:

1) without protective gear (bare-headed),
2) with each of the six combinations of protective gear mentioned above,
3) in each of three ejection seats (F-15, F-16, and F-18).

In all, 21 test conditions were measured for each subject in Phase I. In Phase II, 14 test conditions were measured for each subject.

TEST PROCEDURE

After the initial in-brief, anthropometric measurement, and landmark identification, each subject donned the appropriate size flight suit and harness and was seated in the first of the ejection seats. The seats were oriented as they would be in actual aircraft. Each of the four body poses were demonstrated for the subjects. Subjects practiced each body posture before data collection began. Each pose is described below.

Uplook Poses

Horizontal Forward Line-of-Sight

The "horizontal forward line-of-sight," (or "straight ahead") is defined as: the subject's line of sight parallel to the aircraft waterline with respect to the seat pan/seat back angle. The horizontal forward line of sight (Pose 1) is used as the base ray of the uplook angle. In order to achieve horizontal forward, a large, upright mirror was placed directly in front of each seat, three to five feet from the seat. Subjects were instructed to look directly into the reflection of their own eyes in the mirror in order to achieve horizontal forward. (See Figure 3.)

The Pose 1 Repeatability Test

Initial pre-testing included a Pose 1 repeatability test. Anthropometrically diverse pre-test subjects participated in the repeatability testing. Each pre-test subject was seated in an ejection seat and asked to indicate when horizontal forward had been achieved (using the method described above); horizontal forward was then photographed. The subject then got out of the ejection seat and took a break which lasted anywhere from one to five minutes. The subject then returned to the ejection seat to repeat the procedure. Each subject was photographed in horizontal forward position a minimum of five times.

The repeatability test photos were then reviewed. Because the "zero" line (which corresponds to the aircraft waterline) was marked in a visible location on each ejection seat, it serves as one ray of the angle used to determine repeatability of the pose. The pre-marked anatomical landmarks are used to create the other ray, and the horizontal forward "angle" is determined for each iteration of each subject. The angles were then compared for repeatability, and Pose 1 was determined to be repeatable within +/- one degree.

The Other Poses

In Pose 2 (restrained uplook), the subject was instructed to keep his or her shoulders and back (upper torso) in contact with the ejection seat. The restraint system inertial reel was locked. While the shoulders and upper torso were kept against the seat, the subject directed his or her forehead toward the ceiling in an attempt to achieve the 90-degree uplook angle. Subjects were instructed to use the maximum head/neck rotation afforded by each respective seat. (See Figure 3.)

For Pose 3 (maximum restrained uplook), the inertial reels remained locked but the subject was instructed, in part, to do "whatever is necessary" to achieve 90-degree uplook in the vertical plane. This means that the subject was not required to maintain contact between the upper torso (shoulders and back) and the seat. If the subject needed to lean forward in the seat in order to arch his or her back, the subject was encouraged to do so. The goal of Pose 3 is to attempt to achieve 90-degree uplook in the vertical plane. The method of achievement was left largely to the discretion of the individual subject. (See Figure 3.)

Phase I also incorporated a test of the repeatability of Poses 2 and 3. These repeatability tests were conducted in the same manner as that of Pose 1, and were conducted on 50 of the Phase 1 subjects. Results of the repeatability testing showed Poses 2 and 3 to be repeatable to +/- 3 degrees.

Amendment of the Phase I Test Plan

Early Phase I testing included the three poses described above. As soon as possible after commencement of testing (after 12 subjects were tested), a pilot from Nellis Air Force Base, Nevada, was brought in to determine how realistic the test poses were. The pilot suggested that the maximum uplook pose was unrealistic, especially under high-g conditions. He then suggested allowing experienced pilots to show us the position they believed was possible to achieve under an 8-9 G load. While subjective, this pose seems to be the most realistic of the three for single-circle or double-circle air-to-air encounters. The new pose simulates the limited mobility that occurs during high-g maneuvers (under high-g flying conditions). After some discussion, it was decided that this new pose would be added to the test as a fourth pose (see Figure 4). While we attempted to describe the effects of high-G environment and the head positions that were possible to the civilian subjects, the data were not repeatable and standard deviations for that part of the sample were very large. For that reason, pose 4 data are only reported for the pilot sample.

Photography

Photographic slides were taken for each condition in each seat with a 35 mm camera placed at 90 degrees to the seat and subject to provide a side view. The slides were projected onto a vertical drawing table so that the scale could be greatly increased. Protractors and rulers were then used to measure the uplook angle for each pose relative to the horizontal forward line-of-sight pose. The angles were measured directly from the landmark rays marked on the subject's face and helmet.

RESULTS

The resulting data are overwhelming because of the large number of conditions that were tested (21 for Phase I, 14 for Phase II). Tables 3 through 6 below summarize the most relevant aspects of the study. Equipment effects are reported as deltas from the current configuration of gear each service uses.

The baseline data does not include the High-G pose (pose 4), because pilots felt the pose was unrealistic when the subject did not wear a helmet. A helmet was required to achieve pose 4, and pilots did not wear helmets during baseline data collection.

Also, pilots from the 57 TG were not measured in the F-16 seat. This seat was omitted in order to speed data gathering on pilot subjects (complete data sets required nearly three hours per subject). Pilots were only available for a limited time.

TABLE 3
BASELINE CONFIGURATION
(DEGREES FROM HORIZONTAL)
FLIGHT SUIT ONLY - NO HELMET

		PILOT - MALE		NON - PILOT MALE		NON - PILOT FEMALE	
		MEAN	SD	MEAN	SD	MEAN	SD
F-15	uplook	53.6	10.4	44.2	7.2	40.8	8.8
	max	71.8	8.2	56.5	7.2	60.3	9.3
F-16	uplook	not gathered		60.4	10.1	59.5	10.5
	max			73.7	10.6	76.6	11.3
F-18	uplook	51.0	9.9	37.9	8.4	34.1	10.6
	max	79.2	11.0	63.8	14.6	62.7	13.3

TABLE 4
TYPICAL CONFIGURATION
(HGU-55/P HELMET- NO LPU)

		PILOT - MALE		NON - PILOT MALE		NON - PILOT FEMALE	
		MEAN	SD	MEAN	SD	MEAN	SD
F-15	uplook	50.4	7.6	44.4	7.4	37.2	8.6
	max	67.2	8.1	64.5	9.3	61.9	7.2
	high-g	51.0	10.7	n/a		n/a	
F-16	uplook	not gathered		56.1	6.5	51.4	9.2
	max			72.4	12.3	71.2	7.4
F-18	uplook	43.5	10.0	33.5	9.2	29.6	9.6
	max	64.0	8.3	61.0	11.9	61.3	9.2
	high-g	44.3	13.7	n/a		n/a	

TABLE 5
RECOMMENDED USAF DATA
HGU-55/P, MBU-12/P F-15 SEAT

A. UPLOOK= 50.4 DEGREES
B. MAXIMUM UPLOOK = 67.2 DEGREES
C. HIGHR G POSITION = 51 DEGREES

FOR UPLOOK
ADDING THE LPU, LOSSES = 3.0 DEGREES
SWITCHING TO THE HGU 86/P, GAINS = 2.6 DEGREES
THE F-16 SEAT AVERAGED 11.9 DEGREES BETTER THAN THE F-15 SEAT
FEMALE SUBJECTS AVERAGED 6.8 DEGREES LESS THAN MALES

FOR MAXIMUM UPLOOK
ADDING THE LPU, LOSSES = 7.3 DEGREES
SWITCHING TO THE HGU 86/P, GAINS = 5.5 DEGREES
THE F-16 SEAT AVERAGED 6.3 DEGREES BETTER THAN THE F-15 SEAT
FEMALE SUBJECTS AVERAGED 3.3 DEGREES LESS THAN MALES

FOR HIGH G POSITION
ADDING THE LPU, LOSSES = 4.7 DEGREES
SWITCHING TO THE HGU 86/P, GAINS = 3.0 DEGREES
THE F-16 SEAT AVERAGED 6.9 DEGREES BETTER THAN THE F-15 SEAT

TABLE 6
RECOMMENDED USN DATA
(HGU-55/P, MBU-12/P, F-18 SEAT)

A. UPLOOK = 43.5 DEGREES
B. MAXIMUM UPLOOK = 64.0 DEGREES
C. HIGH G POSITION = 44.3 DEGREES

FOR UPLOOK
ADDING THE LPU, LOSSES = 1.6 DEGREES
SWITCHING TO THE HGU 86/P, GAINS = 1.3 DEGREES
FEMALES AVERAGED 4.7 DEGREES LESS THAN MALES

FOR MAXIMUM UPLOOK
ADDING THE LPU, LOSSES = 3.3 DEGREES
SWITCHING TO THE HGU 86/P, GAINS = 4.7 DEGREES
MALE AND FEMALE RESULTS WERE SIMILAR

FOR HIGH G POSITION
ADDING THE LPU HAS NO EFFECT
SWITCHING TO THE HGU 86/P, GAINS = 1.6 DEGREES

DISCUSSION

One of the most surprising results of this study is the large difference in uplook capability between pilot and non-pilot test subjects. For the uplook and maximum uplook poses, pilots averaged approximately 12 degrees more than the non-pilot males and 15 degrees more than non-pilot females. For the high-G pose, up-angle for pilots was roughly 20 degrees greater than for non-pilots. For this reason, the data in tables 5 and 6 are for the most part based upon pilot data. Non-pilot data were only used to compare male/female differences, and to compare the F-15 to the F-16 seat.

Our interpretation of these differences is that they are due to motivation, an understanding of single-circle and double-circle air-to-air engagements, and experience

with the protective equipment. This raises an interesting question for other research studies where non-pilot performance data are used to represent pilot performance.

Standard deviations for the sample ranged from 7 to 14 degrees for all measures. Since it is a subjective pose, the High-G pose had the highest standard deviations (as expected). This was especially true of the non-pilot subjects. For the other poses, the ranges of standard deviations were similar for pilots and non-pilots.

Another interesting result was the loss of uplook capability in the NACES seat, particularly in the high-G position. This is due to the way pilots braced their heads against it when assuming the high-G posture. The headbox for the NACES seat is forward of the plane of the seat back. Early head/helmet contact with the headbox reduced uplook capability. Similarly, the extreme seat back angle of the F-16 allowed pilots greater uplook than in the F-15 configuration for the same reason.

Protective gear also reduced uplook (as expected). Chemical protective equipment was not used in this study because there are so many different types in use and under development in the USAF and USN. We expect that CBR gear will further reduce uplook capability.

The attempt to find a relationship between body size and uplook capability was unsuccessful. The correlations between anthropometric measurements and ranges of motion were insignificant. However, one subject with a very short Sitting Height noticed that as her head rotated up, the back of her helmet quickly contacted the restraint system of the ACES II seat. This caused her helmet to shift forward on her head. While this event did not affect her angle of uplook to a great extent, it may have affected her ability to maintain vision through a helmet mounted visual system. While anthropometric correlations were not obvious from the data, there still may be size-related problems with helmet mounted systems.

APPENDIX A

ANTHROPOMETIC DIMENSION DESCRIPTIONS

01. Weight - the subject stands on scales (nude or wearing lightweight undergarments) with the feet parallel and the weight distributed equally on both feet. This dimension is *estimated by the subject* or measured with a *scale.*

02. Stature - the subject stands erect looking straight ahead with the line of vision parallel to the floor. The arms are relaxed at the sides, and the heels are together with the weight distributed equally on both feet. The vertical distance is measured between the standing surface and the top of the head. This dimension is measured with an *anthropometer.*

03. Sitting Height - the subject sits erect on a flat surface looking straight ahead with the line of vision parallel to the floor. The vertical distance is measured between the sitting surface and the top of the head. This dimension is measured with an *anthropometer.*

04. Eye Height, Sitting - the subject sits erect on a flat surface looking straight ahead with the line of vision parallel to the floor. The vertical distance is measured between the sitting surface and a corner of the right eye. This dimension is measured with an *anthropometer.*

05. Neck Circumference, Base - the subject stands erect looking straight ahead with the line of vision parallel to the floor. The arms are relaxed at the sides. The circumference of the neck is measured at the level of the juncture of the neck with the shoulders. The level of this circumference is established by laying string tie or a tape around the base of the neck. This dimension is measured with a *tape measure.*

06. Head Circumference - the maximum circumference of the head is measured in a front-to-back plane with the tape passing just above the bony brow ridges and over the most protruding point of the back of the head. This dimension is measured with a *tape measure.*

07. Head Length - the maximum straight line is measured between the most protruding point of the forehead between the brow-bridges and the back of the head. This dimension is measured with a *spreading caliper.*

08. Head Breadth - the maximum horizontal breadth of the head above the ears is measured. This dimension is measured with a *spreading caliper.*

09. Bitragion Breadth - the straight-line distance is measured between the right and the left tragion. (Tragion is the point even with the top of the cartilaginous flap at the front of the ear joins the head). This dimension is measured with a *spreading caliper.*

10. Bizygomatic Breadth - the maximum horizontal distance is measured across the face between the upper cheek bones (zygomatic arches). This dimension is measured with a *spreading caliper.*

11. Menton-Sellion (Menton to Nasal Root Depression) Length - the subject closes the mouth with the teeth lightly together. The vertical distance is measured between the underside of the tip of the chin (menton) in the midline of the face and the point of deepest depression at the top of the nose between the eyes. This dimension is measured with a *spreading caliper.*

12. Neck Length Anterior - the vertical surface distance is measured between the juncture of the chin and neck and the top of the breast bone. (Anterior is at or toward the front of the body or body part). This dimension is measured with a *tape measure.*

13. Neck Length Posterior, Inion - the vertical surface distance is measured down from the tip (inion) of the prominent bump of the lower center of the back of the skull to the base of the back of the neck. This dimension is measured with a *tape measure.*

14. Neck Length Posterior, Nuchale - the vertical surface distance is measured down from the lowest point (nuchale) on the center of the back of the head where the skull can still be felt among the neck muscles to the base of the back of the neck. This dimension is measured with a *tape measure.*

15. Interpupillary Distance - the subject looks straight ahead. The straight-line distance is measured between the centers of the pupils. This dimension is measured with a *pupillometer.*

16. Interpupillary Distance, Right - the subject looks straight ahead. The straight-line distance is measured from sellion (nasal root depression) to the right pupil. This dimension is measured with a *pupillometer.*

17. Interpupillary Distance, Left - the subject looks straight ahead. The straight-line distance is measured from sellion (nasal root depression) to the left pupil. This dimension is measured with a *pupillometer.*

ANTHROPOMETRIC DATA SHEET

DATE ______________________

SUBJECT NUMBER ______________

NAME ______________________

RANK ______________________

DATE OF BIRTH ______________

AGE (AT LAST BIRTHDAY) ______

RACE: W B A H Other

SEX: M F

HGU-55/P SIZE: Med Lrg XL

HGU-86/P SIZE: Sm Med Lrg

AF SPECIALTY CODE __________

MAJCOM ____________________

DUTY STATION ______________

MASK MBU-5/P MBU-12/P

MASK SIZE: Sh Reg Lng XLng

AIRCREW: Yes No

IF AIRCREW, are you:

RATED ☐

NON-RATED ☐

AIRCRAFT TYPE: ______________

FAMILIAR WITH NVS: Yes No

HIGH G_Z EXPERIENCE? Yes No

==

DO NOT WRITE BELOW THIS LINE

SCAN FILENAME(s):

______________________ (unencumbered)

______________________ (helmet/helmet and mask)

MEASUREMENTS (*mm*):

Weight (lbs) ________

Stature ________

Sitting Height ________

Eye Height, Sitting ________

Neck Circumference, Base ________

Head Circumference ________

Head Length ________

Head Breadth ________

Bitragion Breadth ________

Bizygomatic (Face) Breadth ________

Menton-Sellion Lth ________

Neck Lth Anterior ________

Neck Lth Posterior - Inion ________

Neck Lth Posterior-Nuchale ________

IPD (total) ________

IPD - right ________

IPD - left ________

Measurer ______________________

Recorder ______________________

APPENDIX B

Phase II:

The Angle Range of Motion Data Collection Report

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MEASURING UPLOOK ENVELOPES

IN THE F-15 AND F-18

OBJECTIVE:

To quantify the head/helmet movement envelopes for F-15 and F-18 pilots while wearing various combinations of PPE. This study was conducted concurrently with another study where planar uplook angles were measured photographically.

METHOD:

This experiment used a full factorial design, measuring all combinations of the following conditions:

- Two seats
- Two helmets
- With and without life-preserver
- Two envelope directions
- Two envelope types

VARIABLES:

- Seat Type
  For a particular condition, a subject was seated in either an ACES II seat from an F-15, or a NACES seat from an F-18.

- Helmet Type
  For a particular condition, a subject wore either an HGU-55P or an HGU-86P helmet.

- Life Preserver on/off
  For a particular condition, a subject either wore a life preserver or did not.

- Envelope Type
  Two types of envelope were measured, the Maximum Envelope and the Estimated Hi-G Envelope. The Maximum Envelope is the curve describing maximum voluntary head movement in each direction. The Estimated Hi-G Envelope is the curve describing estimated maximum voluntary head movement under Hi-G conditions.

- Envelope Direction
  For a particular condition, a subject rotated his head either to the left or to the right.

- Horizontal Forward Line-of-Sight
  The subject's line of sight parallel to the aircraft waterline with respect to the seat pan/seat back angle. This condition was measured each time the subject

changed helmets.

EQUIPMENT:

Flock of Birds System

The Flock of Birds (FOB) System is a 3D location-orientation measuring device which bases its measurements on magnetic field strength and orientation. A central transmitter generates magnetic fields within an 8-foot hemispherical region. Small sensors (called bird sensors) can then be placed into this generated field, and can detect their location and orientation relative to the field source (i.e., the transmitter). These data can be collected at a maximum rate of 100 Hz. Because the FOB System was used for measuring location and orientation, several characteristics of this system had to be taken into account during setup:

Hemisphere/distance considerations: Without significant reprogramming, the FOB System can obtain data in a single hemisphere with an eight-foot radius. Because of this, both seats had to be located in such a way that all sensors at all times were within the same hemisphere. The seats were positioned back-to-back, while ensuring that the side of each seat on which the bird sensor was mounted was closest to the FOB transmitter (see figure 1). Distances from the seats to the transmitter were chosen to ensure that all bird sensors were within 2-6 feet of the transmitter at all times.

Ambient electromagnetic (E-M) Activity: Earlier work on the FOB System has shown that ambient electromagnetic (E-M) activity can adversely affect the accuracy of the FOB System. Consequently, the entire experiment was set up in an aircraft hanger, where there were no sources of E-M within 20 feet of the experimental station.

Mounting the bird sensors: To avoid having to precisely align the seats relative to the transmitter, a bird sensor was mounted on each seat. A convenient vertical structure was chosen on each seat, and a sensor was mounted using a digital inclinometer (accurate to .1 degrees) to ensure that the y- and z-axes of each bird sensor were parallel to the horizontal alignment of the seat. In each case, then, the x-axis of the seat sensor was parallel to the vertical direction; the y-axis was parallel to the waterline; and the z-axis was parallel to the buttline of the aircraft seat.

Next, because the orientation of the helmet was desired, sensor mounting blocks were attached approximately to the top center of each helmet. A bird sensor could then be quickly attached (via two mounting screws) to whichever helmet fit the subject.

F-15 Seat

This was an ACES-II seat removed from an F-15, and positioned on a frame at 15 degrees relative to gravity (the same way the seat was mounted in the aircraft).

F-18 Seat

This was an NACES seat removed from an F-18, and positioned on a frame at 22 degrees relative to gravity (the same way the seat was mounted in the aircraft).

HGU-55/P

The HGU-55/P is the three-size, standard issue Air Force fighter/attack aircrew helmet. The 55/P was tested with the MBU-12/P oral/nasal oxygen mask, which is the current issue mask.

HGU-86/P

The HGU-86/P is a prototype helmet developed by the F-22 Special Project Office (SPO) for use by F-22 aircrew members. The HGU-86/P was designed to be a stand-alone equipment item, and was tested as such during the Head Tilt Range of Motion and Angular Range of Motion testing. Although the F-22 SPO has developed an oxygen mask to be worn by F-22 aircrews, a prototype of the mask was not available for testing.

LPU-21B/P Life Preserver

The LPU-21B/P flotation assembly consists of two independent flotation chambers. One chamber consists of the left waist lobe joined by a tube to the right collar lobe. The other chamber consists of the right waist lobe joined by a tube to the left collar lobe. The fire-retardent aramid cloth casing assembly is secured around the wearer's waist by the front connector assembly.

SUBJECTS:

21 male USAF Pilots

PROCEDURES

Subjects were instructed according to movement type:

Horizontal Forward Line-of-Sight

A large mirror was placed directly in front of each seat, at a maximum distance of 3-5 feet from the seat. Subjects were instructed to look directly into their eyes in the mirror in order to achieve horizontal forward (Pose 1 in the larger study). HTR incorporated a test of the repeatability of Pose 1. Results of the repeatability testing showed Pose 1 to be repeatable, and repeatability testing was subsequently discontinued during the ARM testing.

Maximum Envelope

For the *Maximum Envelope, Right* the subject was instructed to limit the motion of his torso (shoulder to waist) in order to isolate the head/neck range of motion. The subject started in the horizontal forward line-of-sight pose (see above). From that position, the subject dropped his chin to his chest as far down as neck flexion would allow. The subject then rotated his head up and to the right, while keeping his chin as close to his

chest as possible. This motion continued until the subject achieved maximum right flexion, the head was level, and in line with the right shoulder. The subject then tilted his head back and rotated his chin to the front until he was looking straight up (directly overhead). Keeping his head tilted back, he then turned his chin to the left until his head was level and in line with his left shoulder. The subject continued the motion past the chin-to chest point, and returned to the starting point (the horizontal forward line-of-sight pose). The *Maximum Envelope, Left* is the complement of *Maximum Envelope, Right.* The pilot traced the envelope by rotating his head up and to the left, rather than up and to the right. The pilot hit the same six points as in the right envelope, but the motion was from left to right instead of from right to left as in the first envelope.

Estimated Hi-G Envelope

For the *Estimated Hi-G Envelope, Right* the subject was instructed to limit the motion of his torso (shoulder to waist) in order to isolate the head/neck range of motion. The subject started in the horizontal forward line-of-sight pose (see above). From that position, the subject dropped his chin to his chest until his head was in a position that he estimated corresponded to maximum downward neck flexion in a Hi-G environment. The subject then rotated his head up and to the right, while keeping his chin as close to his chest as he estimated would be possible in a Hi-G environment. This motion continued until his head was in a position that he estimated corresponded to maximum right neck flexion in a Hi-G environment. The subject then tilted his head back and rotated his chin to the front, while keeping his chin as far away from his chest as he estimated would be possible in a Hi-G environment, until his head was in a position that he estimated corresponded to maximum neck extension in a Hi-G environment. Keeping his head tilted back, he then turned his chin to the left, while keeping his chin as far away from his chest as he estimated would be possible in a Hi-G environment, until his head was in a position that he estimated corresponded to maximum left neck flexion in a Hi-G environment. The subject then rotated his head down and to the right, while keeping his chin as close to his chest as he estimated would be possible in a Hi-G environment, and finally returned to the starting point (the horizontal forward line-of-sight pose). The *Estimated Hi-G Envelope, Left* is the complement of *Maximum Envelope, Right.* The pilot traced the envelope by rotating his head up and to the left, rather than up and to the right. The pilot hit the same six points as in the right envelope, but the motion was from left to right instead of from right to left as in the first envelope.

DATA ANALYSIS

As mentioned earlier, one bird sensor was placed onto the helmet the subject was wearing, while a second one was attached to the seat in such a way that this sensor was directly related to the seat geometry. Because each sensor provides data relating its orientation relative to the transmitter, the data from these two sensors could then be used to determine the orientation of the helmet relative to the seat.

In addition, since the information being sought is the orientation of the line-of-sight relative to the seat, a relationship between line-of-sight and helmet orientation had to be derived. The "straight-ahead" poses (see Figure 3 in the main text) were used to develop this relationship.

Definitions:

Coordinate Systems (see figure 1):

S: The orientation of the coordinate system of the sensor placed on the seat.

H: The orientation of the coordinate system of the sensor placed on the helmet.

SRP: The orientation of the SRP coordinate system.

F: The orientation of the head coordinate system.

T: The orientation of the transmitter coordinate system.

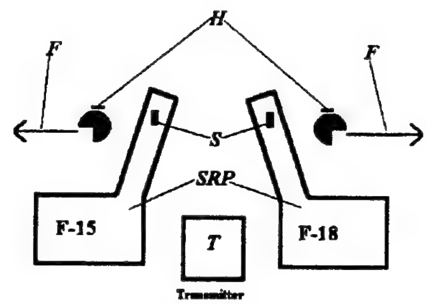

Figure 1: Locations of the various coordinate systems used to determine uplook envelopes.

Transformations:

H: $T \rightarrow H$

S: $T \rightarrow S$

F: $F \rightarrow H$

S': $S \rightarrow SRP$

Calculating Transformations:

H: This is the matrix of data obtained from the helmet sensor.

S: This is the matrix of data obtained from the seat sensor.

S': The seat sensors were placed on the seats so that the sensor coordinate axes were parallel (or anti-parallel) to the coordinate axes of the SRP systems. S' is determined directly from this relationship:

$$\mathbf{S'} = \begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & 0 & 0 \end{pmatrix}, \text{ for the F-15 Seat, and}$$

$$\mathbf{S'} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \text{ for the F-18 seat.}$$

Calculating the Orientation of the Head Relative to the Helmet (F)

When the subject was looking straight ahead, his head was parallel to the **SRP** system [line-of-sight (x-axis) straight ahead, parallel to the waterline; and the normal vector to the plane of symmetry (y-axis) was also parallel to waterline, as well as perpendicular to the line-of-sight]. The z-axis completes a right-handed coordinate system. Consequently **F** can be calculated thusly:

$$\mathbf{F} = \mathbf{H} \cdot \mathbf{S}' \cdot \mathbf{S}''$$

Note that **F** is unique for each subject-helmet combination.

DATA MANIPULATION

As mentioned above, the purpose of the experiment was to quantify the head/helmet movement envelopes, relative to the individual seats. Using data from the FOB system, the orientation of the head, relative to the seat, can be calculated in the form of a 3x3 direction cosine matrix, **A**, such that:

$$F \xrightarrow{\mathbf{A}} SRP$$

The matrix **A** can be determined by using the transformations defined in the **DEFINITIONS** section, above:

$$F \xrightarrow{\mathbf{F}} H \xrightarrow{\mathbf{H}'} T \xrightarrow{\mathbf{S}} S \xrightarrow{\mathbf{S}'} SRP$$

From this mapping chart, **A** can be determined directly:

$$\mathbf{A} = \mathbf{S}' \cdot \mathbf{S} \cdot \mathbf{H}' \cdot \mathbf{F} = \begin{pmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{pmatrix}$$

Because of the way in which the coordinate systems were defined, the first column (**a**= [$a11$, $a21$, $a31$]) of **A** represents the line-of-sight, relative to the seat. And the set of **a** vectors for each set of envelope data represents the various orientations of the line-of-sight vector while the subject's head was rotated through the various envelopes.

Figure 2 shows a typical envelope, as viewed from directly in front of the subject. This figure shows the maximum envelope data for both directions. In this case, subject #154 was in the F-15 seat, wearing the HGU-86P, and not wearing the life preserver. Note that, since the subject began each envelope in the neutral head position, the data points at the beginning of each trial need to be discarded. In addition, since this experiment was not concerned with head declination, all points with a negative vertical direction were also discarded.

After these points were discarded, the data were converted to pairs of azimuthal and elevation angles. Figure 3 shows these pairs for the maximum envelope with no life preserver. The radial distribution of the data about the azimuthal-elevation origin was evident for all envelopes. Because of the way in which these data are distributed, breakdown averages of elevation angles relative to azimuthal angles would contain large variances in elevation angle at the extreme values of azimuth, thereby widening the confidence bands around the estimated average uplook envelope at these extreme values. Thus the data were transformed into polar coordinates (r,φ) of the azimuth-elevation

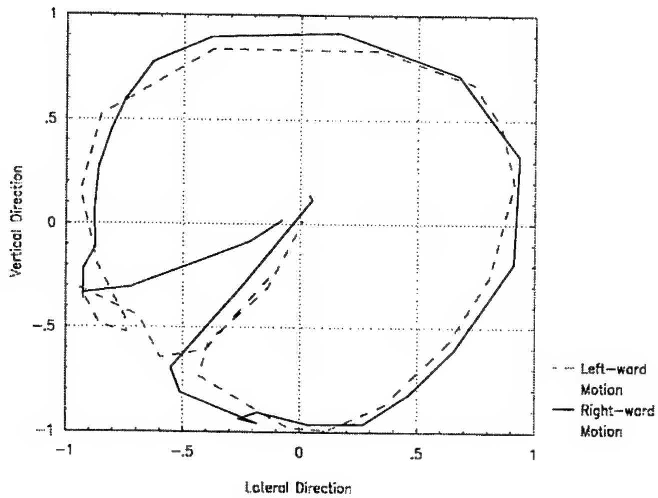

Figure 2: Front view of individual subject's maximum uplook envelope direction cosine vectors.

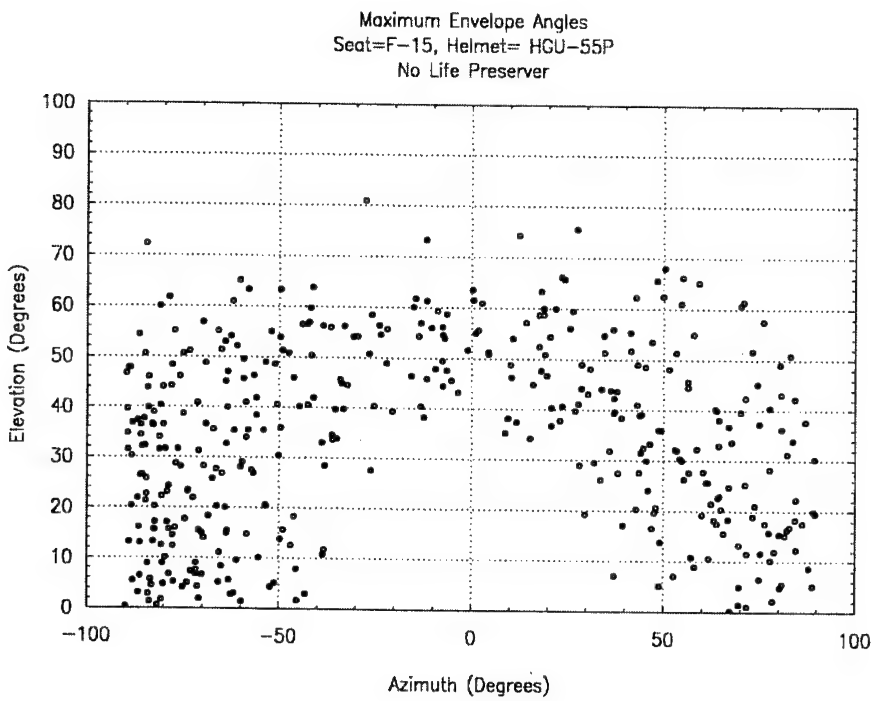

Figure 3: Uplook Envelope Angle Data
All subjects, F-18 seat and HGU-55P helmet combinations.

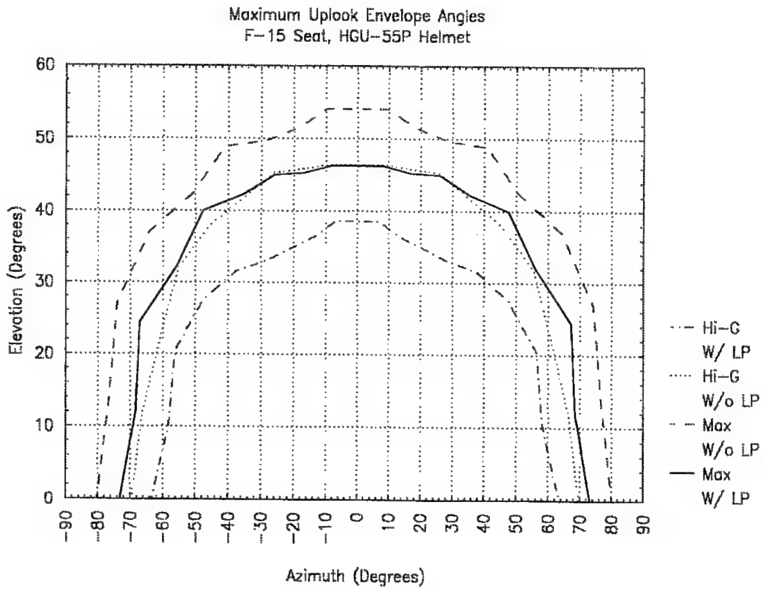

Figure 4: Uplook Envelope Angles (raw averages), F-15 Seat and HGU-55P helmet combinations.

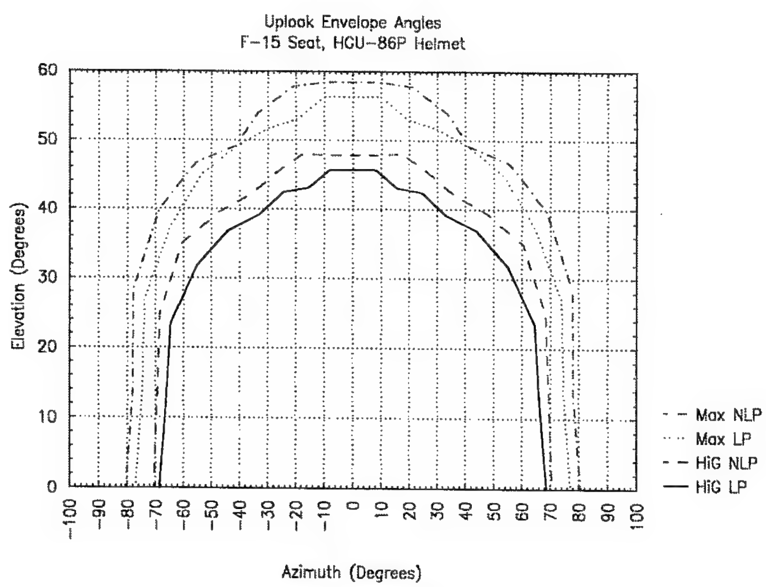

Figure 5: Uplook Envelope Angles (raw averages) F-15 seat and HGU-86P helmet combinations.

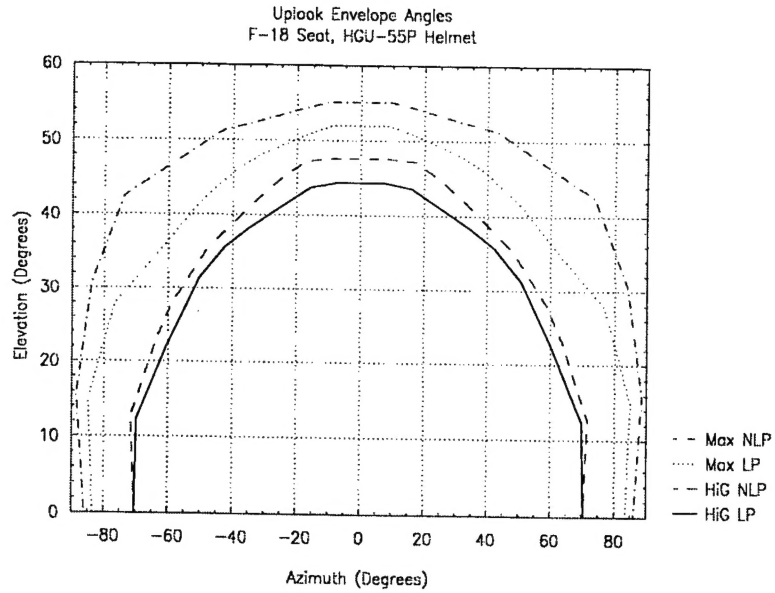

**Figure 6: Uplook Envelope Angles (raw averages)
F-18 seat and HGU-55P helmet combinations.**

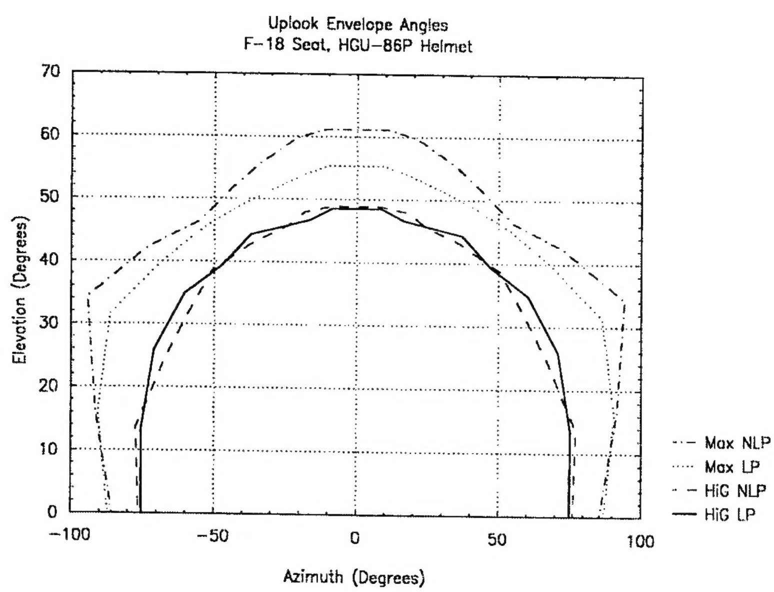

**Figure 7: Uplook Envelope Angles (raw averages)
F-18 seat and HGU-86P helmet combinations.**

Finally, least-squares fits of these data were developed, using the polar angle as the regressor, and the polar coordinate radius as the dependent variable. The r^2 values ranged from .85 to .98 for these regressions. Figures 8 through 11 show the final, smoothed envelope angles.

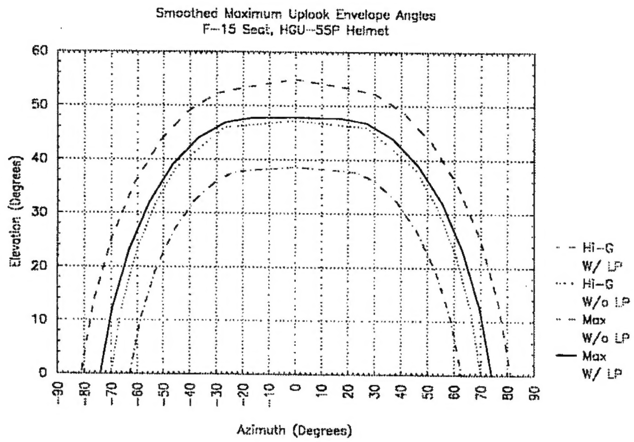

**Figure 8: Uplook Envelope Angles (Smoothed)
F-15 seat and HGU-55P helmet combinations.**

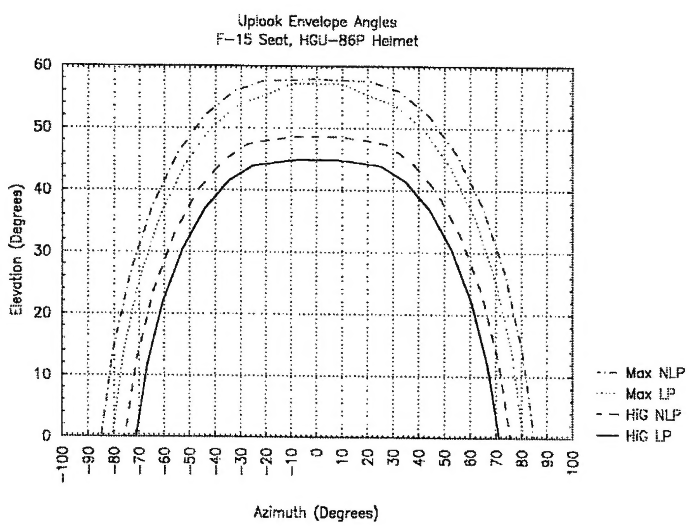

**Figure 9: Uplook Envelope Angles (Smoothed)
F-15 seat and HGU-86P helmet combinations.**

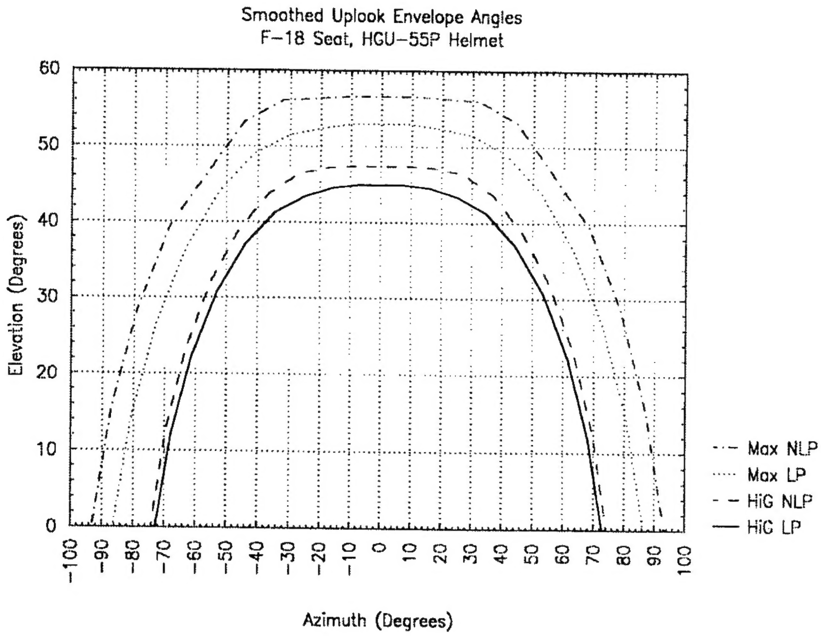

Figure 10: Uplook Envelope Angles (Smoothed)
F-18 seat and HGU-55P helmet combinations

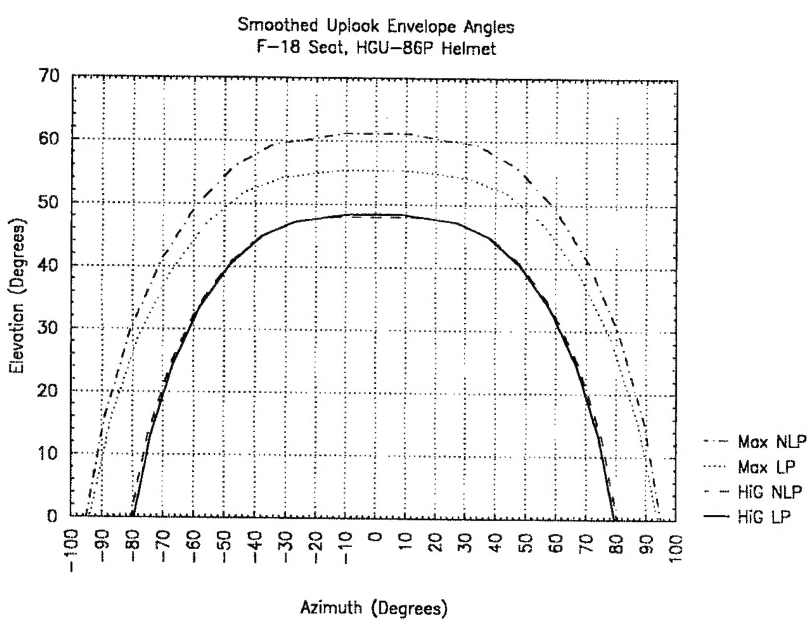

Figure 11: Uplook Envelope Angles (Smoothed)
F-18 seat and HGU-86P helmet combinations

RESULTS

In all cases, the largest envelope obtained by subjects was the Maximum Envelope without the Life Preserver. For the Maximum Envelope, the subjects performance lessened by anywhere from 1-6 degrees, with the maximum decrement occurring during full backwards extension. Similarly, subjects performed 3-5 degrees better when wearing the HGU-86P helmet, as compared to when they were wearing the HGU-55P. This difference was relatively independent of the direction of head movement. When comparing the two seats, the maximum envelopes were very similar, although a statistical comparison of the two was not performed.

The plots of the Estimated Hi-G Envelopes indicate results similar to those discussed above. However, the variability was much greater, with the life preserver affecting performance from 0-10 degrees, the helmet affecting performance from 1-10 degrees, and the seat affecting performance 2-6 degrees.

CONCLUSIONS

Overall, the smallest envelope measured was the estimated Hi-G in the F-15 seat, wearing the HGU-55P helmet and the life preserver. Any helmet-mounted rearward sighting devices, then, should be designed to accommodate this condition. In addition, one should note that in all cases, the ability to look rearward decreases rapidly outside a range of $\pm$ 60 degrees azimuth relative to straight forward.

One aspect not touched upon in this study is the movement of the head inside the helmet. This could be a crucial issue, because if the line-of-sight shifts outside the range of exit pupil, the sighting device will be totally useless to the pilot when it is most needed. More experimentation in this area is needed.